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TECHNICAL NOTE

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ENVIRONMENTAL PROBLEMS OF SPACE FLIGHT STRUCTURES

I. IONIZING RADIATION IN SPACE AND ITS INFLUENCE ON SPACECRAFT DESIGN

Prepared by Louis F. Vosteen in collaboration with the
NASA Research Advisory Committee on Missile
and Space Vehicle Structures

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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PREFACE

The exploration, study, and definition of the environmental conditions which exist in space beyond the earth's atmosphere form an essential part of the current space-age effort. The development of this science is of especial interest to the vehicle structures designer, who must make decisions today that will establish the capability and efficiency of the space hardware in use 5 and 10 years hence. The time, the tools, and the money available for obtaining necessary engineering data concerning space environment are limited. It is therefore of utmost importance that the total national effort be coordinated and directed to bring the maximum returns.

Recognizing the urgency of this situation, the NASA Research Advisory Committee on Missile and Space Vehicle Structures has appointed an Environmental Task Force to review the problems and recommend appropriate action. The result will be a series of definitive reports, each report dealing with an important space-age design environmental problem, which are intended to present the present state of knowledge and to make recommendations regarding the direction of future effort. These reports will be prepared primarily by NASA technical personnel but with the critical assistance of the entire Committee. The subject of the present study is the problem of the natural radiation environment.

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SUMMARY

This report summarizes the present state of knowledge of the natural radiation environment of space and discusses the manner in which the environment may interact with space vehicles. The radiation damage to various materials and spacecraft components is indicated and the selection of materials best suited for use as radiation shields is discussed. The necessity for providing protection against biologically damaging radiation is shown to be of prime concern for manned vehicles.

INTRODUCTION

The problems associated with the flight of vehicles outside the earth's atmosphere are greatly complicated by the presence of ionizing radiation known to exist in space. This radiation may affect the integrity of structural and electrical components, or, in the case of manned vehicles, cause irreparable biological damage to the vehicle occupants.

The purpose of this paper is to provide a summary of the space radiation environment and to describe briefly and simply how the environment may influence vehicle design. The present paper is not intended to replace the many excellent articles which have been written concerning space radiation but only to provide a starting point for the engineer who may not be familiar with the problems that radiation may impose on vehicle design.

The natural radiation environment of space is composed of charged particles and a broad spectrum of electromagnetic radiation. The electromagnetic radiation is of sufficient energy to ionize the earth's upper atmosphere but will not have a significant effect on the properties of inorganic materials or contribute substantially to the radiation dose imposed on occupants of manned space vehicles. For these reasons, it has been omitted from the following discussion.

A number of references are cited for the benefit of anyone who may desire greater detail than this paper provides. In addition, a bibliography is given of other papers of considerable interest which were not cited directly.

SYMBOLS AND ABBREVIATIONS

E	energy
H_α	first spectral line of hydrogen in the Balmer series, wavelength 6,563 Å
N(>E)	number of particles N with energies greater than E
Å	Angstrom unit, 10^{-10} meters
Bev	10^9 electron volts
ev	electron volt
g	gram
kev	10^3 electron volts
Mev	10^6 electron volts
rad	radiation absorbed dose, energy absorption of 100 ergs/g
RBE	relative biological effectiveness
rem	roentgen equivalent man
rep	roentgen equivalent physical; energy absorption of 93 ergs/g

THE ENVIRONMENT

The radiation environment to which a space vehicle may be exposed is comprised of the trapped particles that form the great radiation belts surrounding the earth, the ever-present background of cosmic rays, and the intense particle streams associated with solar flares. Each of the above radiation sources will be discussed in turn to indicate the present knowledge of the radiation environment.

Radiation Belts

Since the verification in 1958 of the existence of the radiation belts, a great deal of effort has been placed on defining them with respect to their spatial distribution, their composition, and their fluctuations with time.

The approximate variation in the composition of the radiation belts with altitude on the geomagnetic equator is shown in figure 1 (replotted from ref. 1). The inner belt is defined by the region of high-energy protons which have a maximum flux at an altitude of about 3,600 km. The outer zone is defined by a region of high-energy electrons which extends down through the lower belt.

Figure 2(a) shows the very familiar figure of the intensity structure of the radiation belts as given by Van Allen (ref. 2). The contours shown in figure 2(a) represent isointensity lines of the counting rate of a Geiger tube (Anton 302) and were based on measurements made during the flights of Explorer IV (1958 Epsilon) between July and October 1958 and Pioneer III (1958 Theta) on December 6, 1958, and were essentially substantiated by measurements made by Pioneer IV (1959 Nu) on March 3, 1959 (ref. 3). Measurements made during August 1959 by an essentially identical instrument aboard Explorer VI (1959 Delta) indicate a marked change in the structure of the outer radiation belt. The counting rate contours indicated by the Explorer VI measurements are shown in figure 2(b) which was taken from reference 4. As figure 2(b) shows, the outer portion of the radiation zones had decreased in intensity and extent from that shown in figure 2(a). In addition, the outer portion of the belt contained two maxima - one at 17,000 km and another at 23,000 km from the earth's geomagnetic axis. It is believed (ref. 4) that figure 2(b) indicates the general condition of the radiation belts during quiet solar periods in contrast to figure 2(a) which was based on measurements made during a period of substantial solar activity. A geomagnetic storm which commenced abruptly on August 16, 1959 (just after the period on which fig. 2(b) was based) further emphasized the temporal nature of the outer portions of the radiation belts. Large changes in the outermost belt were observed immediately following this activity and again on September 3, 1959, when a 2+ solar flare occurred. (Solar flares and their designations will be discussed further in the section "Solar Flares.") Explorer VII (1959 Iota 1) which was launched in October 1959 gave further evidence of variations in the structure of the outer zone. Detailed discussions of the observations made during the flights of Explorer VI and Explorer VII can be found in references 4 to 7.

Measurements of the intensity of electrons in the outer radiation belt as determined by instruments on Explorer XII (1961 Upsilon 1) (ref. 8) are given in table 1. Also shown are the intensities of protons and electrons in the heart of the inner zone as presented in reference 2.

Explorer XII also carried an electrostatic analyzer capable of measuring proton fluxes in the energy range from 0.1 to 20 kev. Preliminary unpublished results of data obtained by Michel Bader of the NASA Ames Research Center indicated a flux of protons of less than 4×10^5 protons/cm^2-sec out to a geocentric distance of 10 earth radii (about 64,000 km) and a random flux of up to 5×10^8 protons/cm^2-sec at energies between 2 and 15 kev between 10 and 13 earth radii. Although the nature of the particles trapped in the earth's magnetic field is fairly well established, the intensity values given in table 1 are considered to be accurate only to about an order of magnitude.

Cosmic Rays

Cosmic rays[1] are an ever-present background of ionizing radiation which appear to originate outside our solar system and arrive in the vicinity of earth with no apparent directionality. The composition of the rays is quite well known and, as described in reference 10, consists of about 85 percent protons, 13 percent alpha particles, and less than 2 percent nuclei of higher-atomic-number particles. The particles which constitute cosmic rays have energies which may reach 10^{18} ev, but, as shown in figure 3 (from ref. 14), their flux is quite low. The intensity of cosmic rays fluctuates with the 11-year cycle of solar sunspot activity, and is highest during years of solar minimum, a time when the magnetic field influence of the sun is the least. At large distances from the earth (beyond 60,000 km) the flux of particles during solar maximum as determined by the space probe Pioneer V is about 2.5 particles/cm^2-sec.

Solar Flares

The radiation source which presently poses the greatest hazard to space flight is from the energetic particles which are emitted from the sun during solar flares. Solar flares are areas of the sun's surface which display a very sharp increase in light intensity - especially in the spectral line at 6,563 Å, the H_α line. Flares almost always appear in conjunction with sunspot groups and are most generally associated with magnetically complex groups (refs. 10 and 11). Table 2 shows the classification of flares as given in reference 12. In recent literature (e.g.,

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[1]Cosmic rays are often referred to as galactic cosmic rays in order to distinguish them from solar flare particles which are sometimes called solar cosmic rays.

appendix A of ref. 10) the "plus" designation also has been applied to class 2 flares of unusual brightness.

In 1946, Forbush (ref. 13) suggested that streams of energetic particles may be ejected from the sun during solar flares. This was based on observed increases in the intensity of cosmic rays as indicated by monitoring instruments at ground level and led to the term "solar" cosmic rays. From 1937 until 1956 only five instances of cosmic ray increases associated with a solar flare were noted and hence it was concluded that these events were rare. Since that time, other means have been developed to detect an influx of charged particles from the sun in the vicinity of the earth. These include observations of changes in the ionosphere, distortion of the earth's magnetic field, and bursts of radio noise from the sun. These measurements coupled with measurements in high-altitude balloons, sounding rockets, deep space probes, and satellites show that solar flare particles are not as uncommon as first discoveries indicated. Few flares, however, eject particles with sufficient energy to penetrate through the shielding of the earth's atmosphere and magnetic field to ground level.

During the eighteen months of the International Geophysical Year (July 1957 to December 1958) a total of 6,762 flares of class or importance 1 or greater was observed (ref. 14). Of these, 21 resulted in observable effects in the lower ionosphere, the high atmosphere, or, at times, at sea level. Flares of the size which generally produce these effects (class 2 or greater) are of great concern especially for manned space flight.

The number of sunspots varies in a rather regular manner in an 11-year cycle. (See, for example, ref. 12.) Because flares are associated with sunspots, it is not surprising to find that the number of observed flares also varies in about the same manner as the number of sunspots. The extremely energetic proton events or solar bursts such as those which resulted in the five ground-level cosmic-ray increases detected between 1937 and 1956 do not appear to follow the same regular pattern as do most solar flares and were observed during periods of increasing and decreasing solar activity.

The composition of the particle streams ejected during flares is approximately the same as that of cosmic rays but may contain a greater percentage of protons. The energies of protons observed during some high-energy events extend up to 20 Bev - an energy sufficient to penetrate over 3 meters of water. Fortunately such events are not too frequent and the flux of particles in the Bev range is rather low. Figure 3 shows the integral energy spectra of protons at specific times during several solar flares as given in reference 9. The spectra of protons in the inner Van Allen belt and that of the galactic cosmic rays are shown for comparison. As is suggested by figure 3, each solar flare must be considered unique in its energy spectrum and intensity variation with time. Dotted lines have been shown for the portions of the spectra which are extrapolated. Information of the type shown in figure 3 has been obtained only in recent years and is not sufficient to permit any general conclusions to be drawn on the time variation of the energy spectra for all flares. From the curves shown for the flare on February 23, 1956, one might infer that the flux of particles in any energy range always decreases with time. The curves for the flare on November 12, 1960, however, show an increase with time of the flux at the lower energies. In reference 15, Bailey has idealized the evolution of a solar proton event in an effort to describe the variations in the integral energy spectra with time. In his idealization, shown in figure 4, the early part of the event is characterized by high energies and low fluxes. As the event proceeds, the flux increases while the maximum energy decreases.

The great intensity of energetic particles in the solar cosmic rays and the extreme penetrating power of particles associated with the very high-energy events presents an acute, if not presently insurmountable design problem. This has led to studies of the probability of solar flare occurrence. One possible method of prediction as proposed by Anderson is given in reference 16. In this reference, a correlation is shown between the size of the penumbral area, which often surrounds sunspot groups, and the observance of solar flares. For purposes of area comparison, Anderson chose the size of the penumbral areas measured around two large sunspot groups 2 days before the proton event of July 7, 1958. At any time that the penumbral area surrounding a sunspot group on the visible disk of the sun exceeded this "critical," a solid line is shown in figure 5 (data from ref. 16). This line is continued until that group leaves the visible disk (even though the penumbral area may have shrunk to less than critical size). When no critical areas were observed, an open box is shown in the figure. The occurrences of solar proton events are shown by plus marks. For the $3\frac{1}{2}$-year interval shown, a solar proton event occurred on only 5 occasions when the penumbral area was considered subcritical. The remaining 33 events occurred during critical periods. In none of these instances did an event occur within 2 days from the time the penumbral area became critical. A continuation of this work is given in reference 17 along with a summary of observable solar characteristics which appear to be associated with flares that produce energetic particle streams. Present methods of prediction have not proven to be completely reliable, and, as noted in reference 17, the problem lies in our very meager knowledge of the physics underlying solar phenomena.

The propagation of solar flare particles through space is believed to take place along magnetic field lines which extend out from the sun about 2 to 5 astronomical units[2]. (See, for example, refs. 18 and 19.) These field lines are essentially radial near the sun, but because of the influence of other fields in space and the sun's rotation, they tend to become curved much like the streams of water from a rotating lawn sprinkler. Geomagnetic storms and other evidence of charged particle streams arriving in the vicinity of the earth are generally associated with flares on the western side of the sun's visible disk; this would be expected for such a mechanism of transport of solar flare particles.

The concept of particles traveling along field lines leads to the possibility that the particles will exhibit some directionality with respect to the local magnetic field. Measurements which have been made to date have not shown this directionality. The measurements, however, were not intended for this specific purpose and are therefore subject to question.

EFFECT OF THE ENVIRONMENT ON SPACE FLIGHT

The effects of ionizing radiation on the accomplishment of missions in space divide logically into two classes. The first is concerned with the deleterious effects of radiation on the vehicle structure or its electrical and mechanical components. The second deals with the effects of radiation on human occupants. The damage threshold or level at which the absorbed radiation dose has a marked effect on materials, electronic components, or man is shown in figure 6 which was taken from reference 20. It can be seen that man is the most sensitive to radiation damage by about one order of magnitude. Of the remainder of the items shown, transistors and electrical components are the most sensitive followed by organic materials and, lastly, metals. The effects of radiation on materials will be considered first.

Effect of Radiation Environment on Materials

The radiation present in space may affect materials in several ways: by sputtering, ionization, or atomic displacements. Sputtering is the removal of atoms from the surface of a material by collision or chemical reaction with bombarding ions or atoms. This mechanism is associated with particle energies of about 10 ev to 1 Mev (ref. 21). Unfortunately, most instruments which have been carried in satellites to date have not been capable of detecting particles in the low-energy range. The estimates of surface material losses due to sputtering vary considerably. Calculations presented in reference 21, for example, which were based on extrapolation of measured fluxes to the low-energy (1-kev) range,

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[2]An astronomical unit is the mean distance between the earth and the sun.

estimate surface losses due to sputtering of about 0.1 Å per year in the lower Van Allen belt and about 100 Å per year due to particle emission from solar flares. Reference 22, on the other hand, indicates that surface losses due to sputtering may be as high as 8,000 Å for certain (admittedly pessimistic) assumptions and will probably lie between 100 and 500 Å. Although these losses are negligible from a structural standpoint, they could be significant for sensitive optical and surface thermal properties.

Plastics, elastomers, oils, greases, glasses, and ceramics are subjected to radiation damage chiefly through ionization. High-energy electrons and protons lose most of their energy by means of ionization, and therefore would contribute to the damage of these materials. In addition, the X-rays or bremsstrahlung produced during the stopping of electrons can produce ionization and will be more penetrating than the electrons themselves.

Radiation damage to metals and semiconductors is generally produced through atomic displacements which may be produced by fast neutrons or protons. In order for a proton to produce an atomic displacement, its energy must be greater than 7A ev where A is the atomic weight of the target material. Electrons may also produce atomic displacement, but the energy required is 8,000A ev. Most space vehicles depend strongly on electronic components for the accomplishment of their missions. For this reason, a radiation dose which would alter the function of these components and therefore jeopardize the mission cannot be tolerated.

Much data exist on the effects of nuclear radiation on electronic components (for example, ref. 23) and some work, such as that reported in reference 24, has been done in facilities which more closely simulate the space environment. Some radiation damage may be of a transient nature and disappear (at least partially) upon removal of the radiation. The extent of this type of damage could also be a function of the incident flux so that simulation of both the flux and energy of space radiation would be required for true evaluation.

Existing data on the effects of ionizing radiation on structural properties indicate that metallic materials are far less sensitive in this regard than the nonmetallic materials. For extended exposures in regions of high radiation flux such as the Van Allen belts, the use of some of the more sensitive plastics as structural components may be limited. Electrical components require consideration from the structural standpoint when it becomes necessary to provide radiation shielding.

Radiation Considerations for Manned Space Vehicles

The sensitivity of man to biological damage from radiation requires that special consideration be given to radiation shielding for manned vehicles. The manner in which radiation interacts with living tissue and produces a particular biological effect is very complex. Determination of radiation effects is further complicated by the fact that different types of radiation, and different energy ranges of the same radiation, react differently as they pass through the body. In addition, the rate at which the dose is administered may have a marked influence on the biological effect. (See ref. 25.)

The basic unit for measuring radiation is the roentgen (r) which is defined as the quantity of X-rays required to produce one electrostatic unit of charge per cubic centimeter of air under standard conditions. Another unit which is also defined by the amount of energy deposited in the material is the roentgen equivalent physical (rep) which denotes an energy absorption of 93 ergs per gram, the energy absorbed by 1 gram of soft tissue exposed to 1 roentgen of X-rays. This is essentially the same as the more modern unit, the rad, which is defined as the amount of radiation required to produce an energy absorption of 100 ergs per gram. One rad of any type of radiation will produce the same energy absorption, but because the biological effects produced by one rad of one type of radiation may not be the same as that produced by one rad of another, a factor called the Relative Biological Effectiveness (RBE) has been introduced. This factor relates the ionization dose of X- or gamma-radiation required to produce a particular biological effect to the dose from another type of radiation required for the same effect. The dose in rad multiplied by the RBE yields a quantity called the roentgen equivalent man (rem) which has significance in terms of biological damage.

The energy, flux, and type of radiation which will be encountered in different regions of space varies, and, therefore, the shielding required will be based on the vehicle's trajectory and the duration of its flight.

Radiation belts.- The trapped radiation is composed predominantly of protons and electrons. The high-energy protons are confined almost exclusively to the inner belt and have energies ranging up to 700 Mev. The flux of energetic electrons ($E > 40$ kev) is substantially higher than that of the protons, but the maximum energy is about 5 Mev.

The principal mechanisms by which energetic protons lose their energy are ionization and inelastic nuclear collisions. Energy loss by ionization can be readily calculated. (See, for example, ref. 26.) The physical processes involved in the production of secondary radiation during inelastic nuclear collisions is extremely complex, however, and do not lend themselves readily to simple calculations. The calculated dose rates due to penetrating protons and secondary neutrons behind various thicknesses of carbon shield in the heart of the inner Van Allen belt as given in reference 27 are shown in figure 7. The figure shows that the contribution of secondary neutrons becomes more significant for the thicker shields.

The basic mechanism for stopping electrons of the energies found in the Van Allen belts is through ionizing collisions with orbital electrons in the target material. As the electrons are decelerated they emit electromagnetic radiation in the form of X-rays called bremsstrahlung. This radiation is more penetrating in matter than the original electrons and will contribute almost all the radiation dose within the vehicle due to electron bombardment. The dose rate in rem per hour that would be encountered in the outer Van Allen belt behind various thicknesses of carbon shielding as given in reference 28 is shown in figure 8. The figure also shows the great reduction in dose rate that can be achieved by adding a small thickness of high-atomic-number material to the inside of the shield in order to attenuate the X-rays. This will be discussed further in the section "Radiation Protection Systems."

Cosmic rays.- Cosmic rays consist primarily of protons whose energies extend upward from about 1 Bev. Although these particles are extremely penetrating, their flux is low. Estimates of the radiation dose due to cosmic rays (for example, refs. 10, 29, and 30) indicate a dose rate of about 15 to 20 milliroentgen per day or a total dose of less than 10 rad per year behind 1 gram/cm^2 of low-atomic-number material. One component of the cosmic rays which may have special biological significance consists of the heavy primaries or nuclei of atoms with atomic numbers up to about 50 (tin). These particles cause very heavy ionization tracks as they come to rest and may be very damaging to particular body cells. Reference 31 states that the RBE of these heavy ions may be as great as 100 for certain areas of the brain.

Measurements of the number of heavy primary ionization tracks in emulsion packs carried on the Manhigh II high-altitude manned balloon flight (ref. 32) indicated about 2.6 hits per cubic centimeter per day. For the total body volume this is about 150,000 hits per day. Reference 33 notes that no adverse neurological symptoms have developed in the pilot of the Manhigh II balloon which was at altitudes above 90,000 feet for over 16 hours. The effects of long-time exposure, however, are still undetermined.

Solar flares.- Like the cosmic rays, the primary component of the energetic particle streams from solar flares consists of protons. As shown in figure 3, the energy spectrum may extend into the Bev range and the flux is several orders of magnitude greater than that of the galactic primaries. Figure 3 also shows that the energy spectra of the protons may vary greatly from one flare to another and also show different variations with time. The biological dose from a solar proton event is determined by considering the time variation of the flux and the energy of the particles. An estimate of the dose from several solar flares as determined by Foelsche (ref. 9) is shown in figure 9. The dose curves have been shown as bands because of the uncertainty associated with the time variation of the spectra especially during the first few hours. The curves show that the high-energy events (such as February 23, 1956) are difficult to shield against because increasing the shield thickness results in only small reductions in dose. The dose from the high flux events (July 14, 1959 and May 10, 1959), on the other hand, decreases faster with shield thickness, but the curves indicate a higher dose for the smaller shield thicknesses than that associated with the event on February 23, 1956.

RADIATION PROTECTION SYSTEMS

From the previous discussion it can be concluded that radiation damage to materials will not have a strong influence on the selection of vehicle structural materials. Consideration must be given, however, to the selection of materials for use as radiation shields. The range of a charged particle - that is, the distance that a given particle of given energy will penetrate into a material measured parallel to its incident direction - is a function of the atomic number of the target material. For materials with an atomic number of 6 (carbon) or greater, the range increases with increasing atomic number. For atomic numbers below that of carbon, hydrogen is far superior to any material on the basis of mass per unit area required to stop a charged particle of given energy. Targets of beryllium and boron, however, require more mass per unit area than carbon. Because of geometrical considerations, a hydrogen shield may not always have the least total weight. Figure 10 (from ref. 28) shows the weight of spherical shields with a constant inner radius and sufficient thickness to just stop protons of the energies shown. The figure shows that liquid hydrogen would make the lightest shield only for the lower energies. For structural reasons, materials such as carbon or aluminum would be more practical even at low energies.

In addition to selecting a material for its ability to stop the primary radiation flux, consideration must be given to secondary production. In the case of electron shielding, the low-atomic-number materials are poor generators of secondary X-rays but at the same time they are also poor attenuators of these penetrating secondaries. High-atomic-number materials, such as lead, are most effective for shielding against X-rays and, as indicated in figure 8, the addition of a thin layer to the inside of a low-atomic-number shield results in a considerable reduction in the radiation dose.

As noted above, the production of secondary particles from high-energy-proton bombardment is a complicated process which is not readily calculated. Beryllium, although only slightly less efficient than carbon for stopping protons, is known to be a good source of secondary neutrons whereas carbon is a poor source of these secondaries. The estimates that have been made of the contribution of the secondary radiation to the total dose behind various shields indicate that secondaries may compose an appreciable part of the radiation within heavily shielded vehicles.

Some electronic components, such as solar cells, cannot utilize the radiation protection afforded by the vehicle wall. Analysis of data from Explorer VI as given in reference 34 indicates that the early failure of the transmitters on Explorer VI was due to radiation damage of the unprotected solar cells. The solar cells on Vanguard I (1958 Beta 2) were covered by about 1/8 inch of glass; this satellite has continued to transmit for over 4 years. Preliminary results from a solar cell damage experiment carried on Explorer XII (ref. 35) showed that the output from unprotected cells fell about 50 percent during the first few orbits of the flight, whereas cells covered by a glass window 3 mils thick showed only a 6-percent drop in output during the entire 113 days that the satellite was transmitting.

Radiation shields for both manned and unmanned vehicles will probably not consist of simple, one material slabs as commonly considered in simple analyses. All material lying between the radiation source and the region of the vehicle under consideration will influence the radiation dose. The amount of additional material required for radiation shielding can be kept to a minimum by proper placement and utilization of the radiation insensitive components of the vehicle.

For manned space flight, extended travel within the Van Allen belts appears to be very impractical because of the large amount of shielding that would be required. Results of calculations given in reference 29 indicate that an equatorial traversal of the Van Allen belts which takes about 2 hours could be tolerated if about 6 g-cm^{-2} of carbon shielding plus a thin layer of lead are provided. By the proper selection of trajectories, it should be possible to reduce the shielding requirements still further.

Solar flare protons constitute the prime radiation hazard for manned flight outside the earth's magnetic field. Calculations of shielding requirements for protection from solar flares require a knowledge of the variation of the energy spectra of the particles with time. Estimates of the dose in rep that would be incurred during several solar proton events are shown in figure 9. The curves do not include dose due to secondary particles but are based on penetrating protons only. Shielding of an entire vehicle cabin for these events may not be required if the crew can take shelter in small heavily shielded areas during the event.

It also may be possible to provide partial body shields for portions of the body which are particularly sensitive to radiation.

The amount of shielding required will be a function of how great a dose can be tolerated on a given mission. Permissible dose rates and total integrated doses have been established for the radiation industry but these values are necessarily conservative and practically eliminate any possibility of decernible damage due to radiation for as long as a 50-year working lifetime. Table 3 lists the recommended doses as given in reference 36. Because present-day space flight involves some risk, the establishment of permissible dose limits should be in keeping with these overall risks and, therefore, would not be expected to be as conservative as the standards for industry. A far more reasonable approach would be to establish limits which would certainly preclude a lethal dose but might in extreme cases permit short-time effects such as skin erythema or slight changes in the blood. The body itself affords some self-shielding to the internal organs. As shown in reference 37 the highest dose occurs at the surface of the skin and may be attenuated considerably as it passes through the body. The eyes, however, offer little self-shielding and are especially sensitive to radiation damage. Therefore, they may require special protection.

Another entirely different approach to the shielding problem is to take advantage of the fact that the ionizing radiation of greatest concern for present space flights consists of charged particles. It is conceivable that these charged particles could be prevented from ever reaching the vehicle by employing a magnetic field to divert them. Such a concept is outlined in reference 38. A comparison of shielding weights for a water shield and a magnetic dipole configuration are shown in figure 11. The calculations for the thickness of water shield required ignored any secondary radiation produced within the shield. A magnetic shield would not generate any secondary radiation because the particles would be diverted rather than stopped. The curves shown tend to indicate that as the shielded volume increases or the maximum energy increases, the magnetic shield becomes more efficient than the water shield. The adverse effects of the magnetic field on instruments, radio communication, and possibly on the human body are problems that seem to preclude the immediate use of such a system. The functioning of the system itself is dependent on the use of super conducting coils and would be an advancement beyond present technology. Concepts of this nature appear promising for future spacecraft and undoubtedly warrant continued study.

CONCLUSIONS AND RECOMMENDATIONS

Many uncertainties exist concerning the definition of the ionizing radiation environment itself and the interaction of the environment with the vehicle. These uncertainties obviously place severe restrictions on the efficient design of space vehicles. In order to overcome these restrictions, the NASA Research Advisory Committee on Missile and Space Vehicle Structures recommends that research be directed toward the following specific areas:

1. Definition of the environment: In spite of the vast amount of information that has been obtained during the past 4 years on the composition and structure of the Van Allen belts, a great deal of uncertainty still exists regarding the energy spectra, the flux, and the spatial distribution of particles which comprise the belts. The energy spectra and flux of low-energy particles in particular are not well defined and can be determined only through additional flight measurements.

The importance of a knowledge of the time variation of both the energy spectra and the directionality of solar flare particles is recognized. Information of this type is best obtained by measurements outside the region of the Van Allen belts - that is, beyond 60,000 km. An orbiting vehicle which would provide measurements over an extended period of time and could measure particle energies and fluxes at regular intervals during several solar proton events would add greatly to the information essential to efficient shield design.

Research directed toward a better understanding of the basic mechanisms underlying solar activity and the formation of solar flares in particular holds the greatest promise for reliable prediction of solar proton events.

2. Interaction of the environment with the vehicle: The extremely high energies of the galactic cosmic ray particles make it difficult to shield them completely. Although their flux is low in comparison to the Van Allen radiation and solar flare particles, they constitute an ever-present radiation background that may become a governing design factor for long-time exposure in regions outside the Van Allen belts.

The long-time biological effects of cosmic ray primaries and the production of secondary radiation from cosmic rays and high-energy-proton bombardment and their biological significance are problems which require further study in order to define shielding requirements.

The use of active shielding in the form of magnetic or electrostatic fields shows promise for long-time missions and warrants continued study.

In summary, it may be concluded that the methods of radiation protection or control necessary for manned space flights of extended duration are not presently in view. Basic research, carefully directed to supply detailed information on the environment and its interaction with materials is necessary to provide the fundamental knowledge needed to effect substantial advances in space radiation shielding design.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 19, 1962.

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TABLE 1.- PARTICLE FLUXES IN THE VAN ALLEN BELTS

	E	Flux
Inner belt; altitude, 3,600 km on geomagnetic equator*		
Unidirectional electrons	>20 kev	$\approx 2 \times 10^9$ (cm^2-sec-ster)$^{-1}$
	>600 kev	$\approx 1 \times 10^7$ (cm^2-sec-ster)$^{-1}$
Omnidirectional protons	>40 Mev	$\approx 2 \times 10^4$ (cm^2-sec)$^{-1}$
Outer belt; altitude, 21,000 km at 15° geomagnetic latitude†		
Omnidirectional electrons	45 kev to 60 kev	$\left(9 {+16 \atop -6}\right) \times 10^7$ (cm^2-sec)$^{-1}$
	80 kev to 110 kev	$\left(8 {+16 \atop -5}\right) \times 10^7$ (cm^2-sec)$^{-1}$
	110 kev to 1.6 Mev	$<18^8$ (cm^2-sec)$^{-1}$
	1.6 Mev to 5 Mev	$(2 \pm 1) \times 10^5$ (cm^2-sec)$^{-1}$
	>5 Mev	$<10^3$ (cm^2-sec)$^{-1}$

*From reference 2.
†From reference 8.

TABLE 2.- CLASSIFICATION OF SOLAR FLARES†

Flare class	Average duration in minutes	Range of area in millionths of sun's hemisphere*	Approximate line-width of H_α in Å at maximum brightness	Approximate central intensity of H_α at maximum brightness, as a fraction of the level of the continuous spectrum
1	17	100-250	2-4	0.8-1.75
2	29	250-600	4-6	1.75-2.1
3	62	600-1200	6-8	2.1-2.4
3+	≈180	>1200	>8	>2.4

†From reference 12, "The Sun and Its Influence" by M. A. Ellison (by permission of The Macmillan Co., New York).

*1 millionth of the sun's hemisphere = 1.17×10^6 sq miles = 3.04×10^6 sq kilometers.

TABLE 3.- MAXIMUM PERMISSIBLE OCCUPATIONAL RADIATION EXPOSURE DOSE VALUES*

	Rem per calendar quarter
Whole body, head and trunk, active blood-forming organs, lens of eyes, gonads	$1\frac{1}{4}$
Hands and forearms, feet and ankles	$18\frac{3}{4}$
Skin of whole body	$7\frac{1}{2}$

*From reference 36.

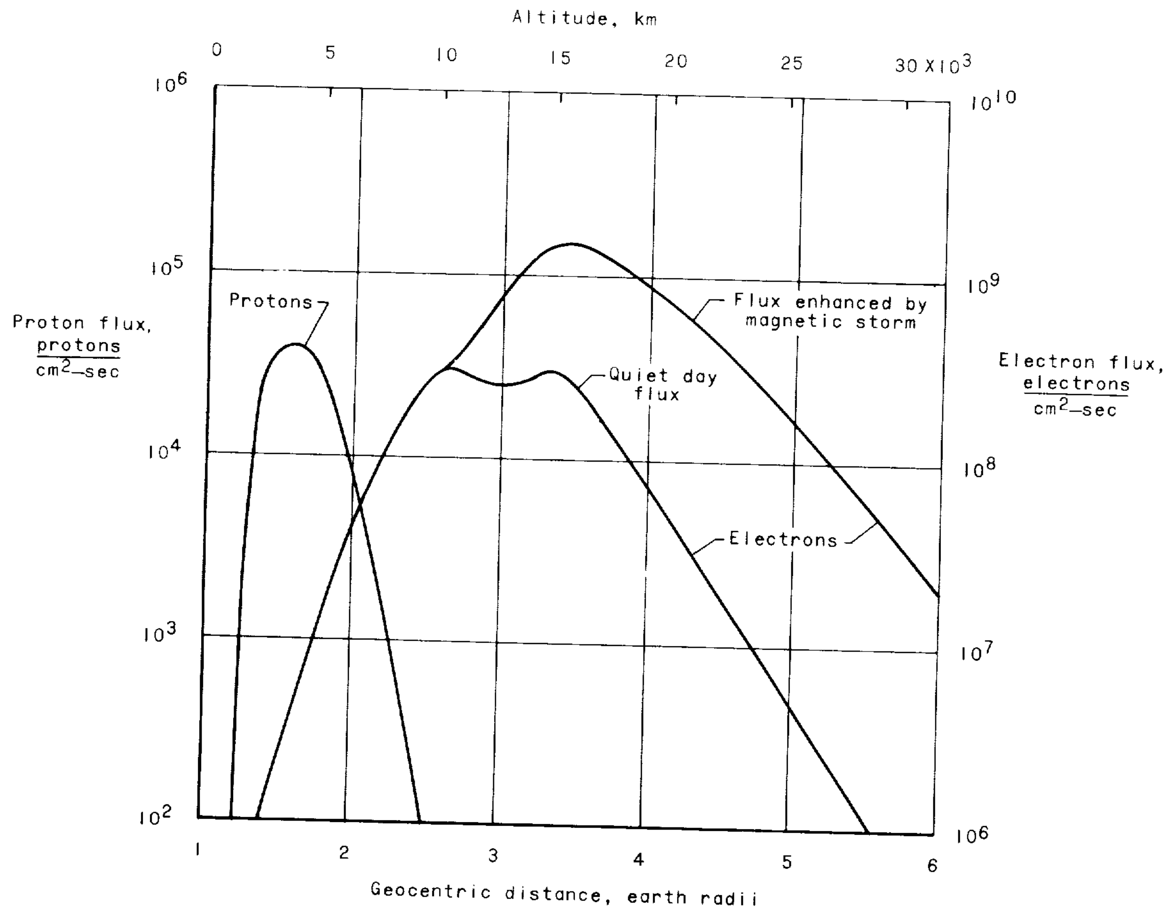
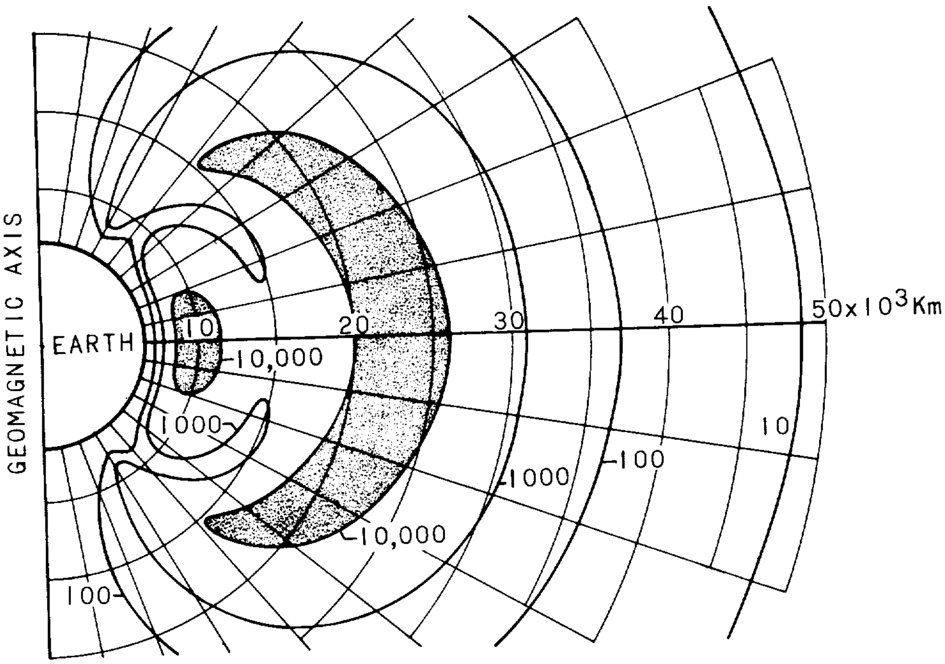
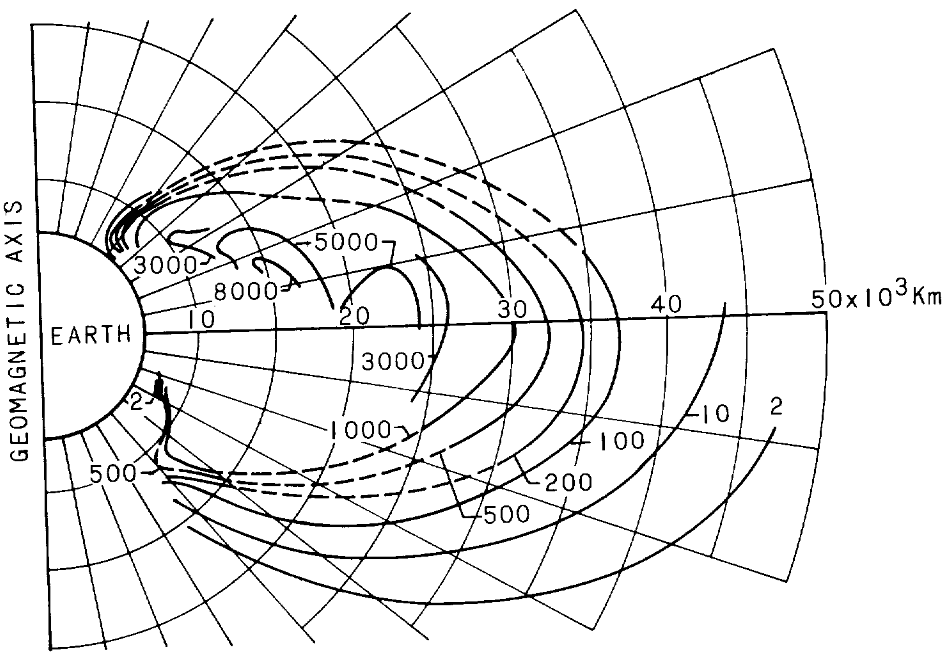


Figure 1.- Approximate variation in the flux of electrons and protons with geocentric distance and altitude in the plane of the geomagnetic equator. (Replotted from ref. 1.)



(a) Contour plotted from reference 2.



(b) Contour plotted from reference 4.

Figure 2.- Counting rate contours for the radiation belts.

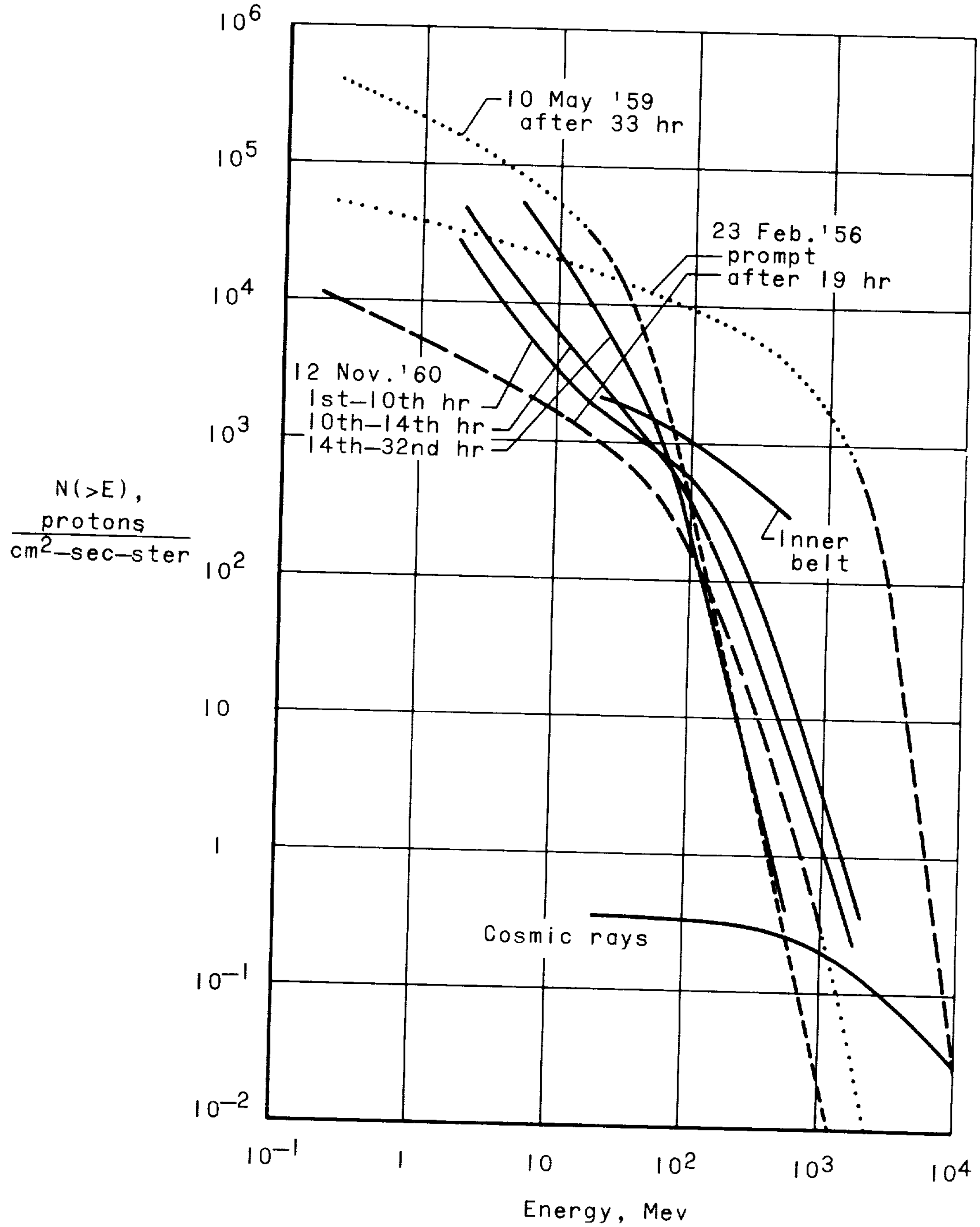


Figure 3.- Integral energy spectra of solar flare protons, cosmic rays (during solar minimum), and protons in the heart of the inner Van Allen belt. Dotted curves indicate extrapolations of measured data. (From ref. 9.)

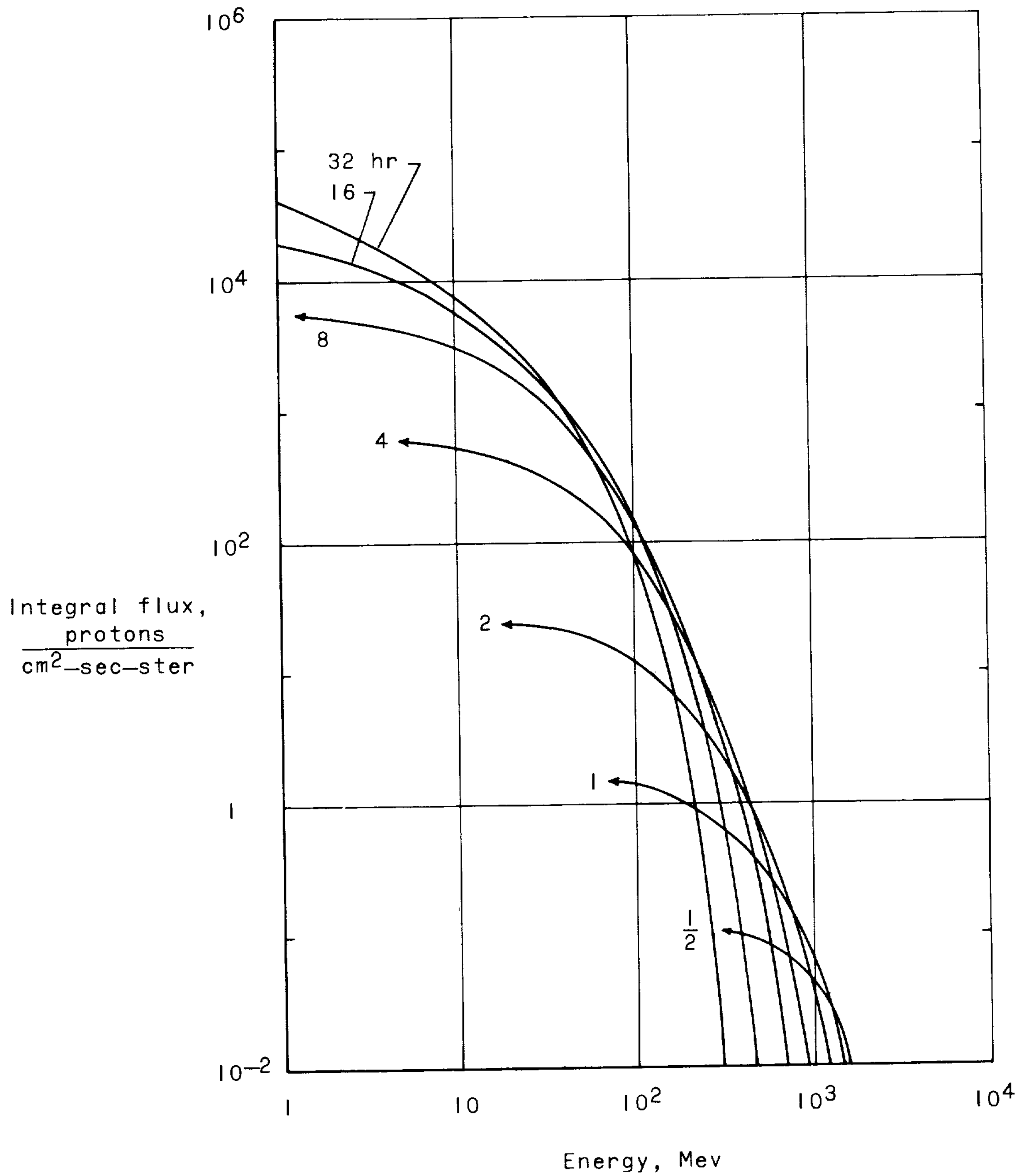


Figure 4.- Idealized time variation of the spectrum of solar flare protons as given in reference 15.

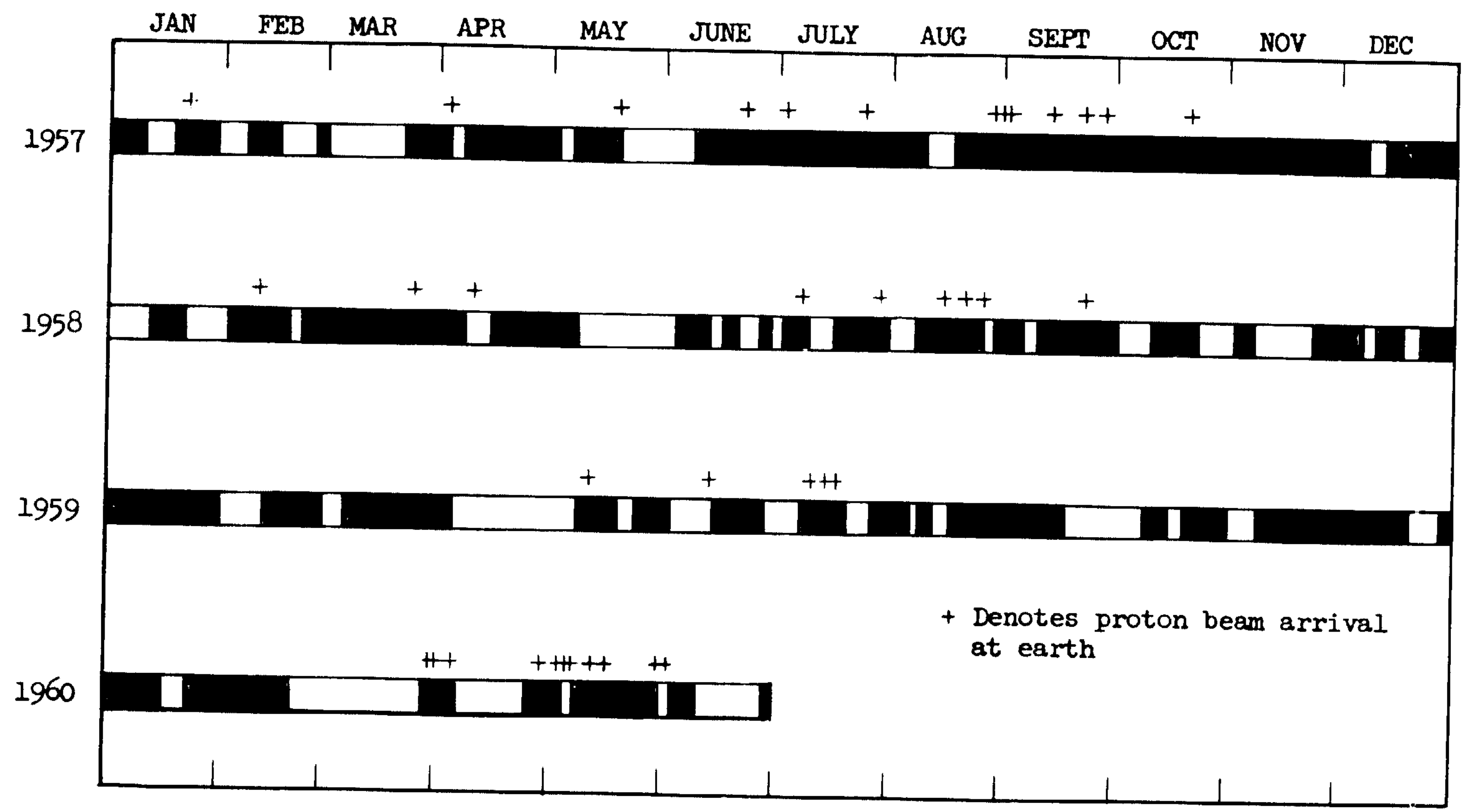


Figure 5.- Prediction of solar flare proton events based on penumbral area. Open areas are periods when the penumbral area was less than critical. (Based on data given in ref. 16.)

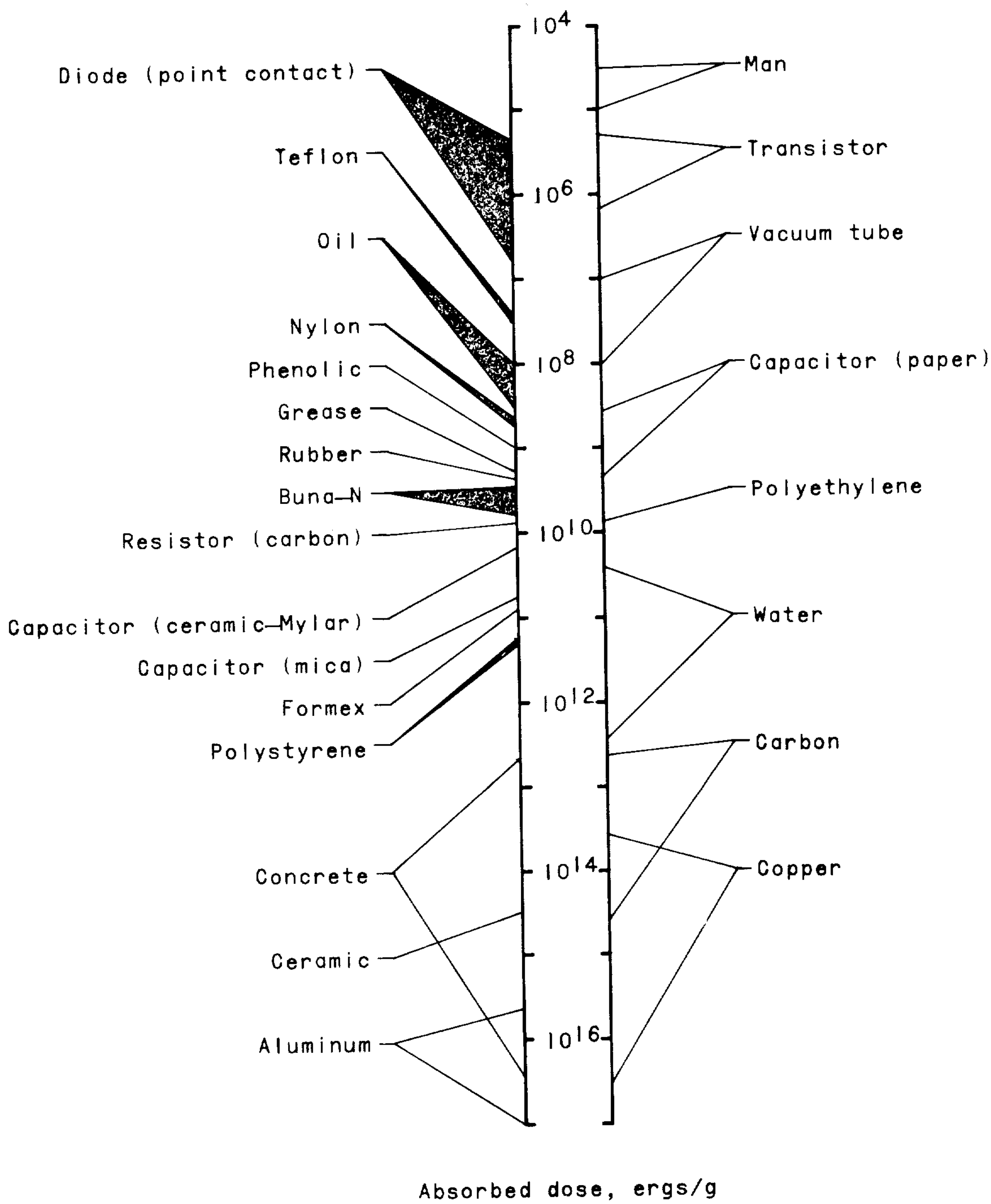


Figure 6.- Threshold dose for functional radiation damage as given in reference 20. (Note that the absorbed dose in rad can be obtained by multiplying the dose in ergs/g by 10^{-2}.)

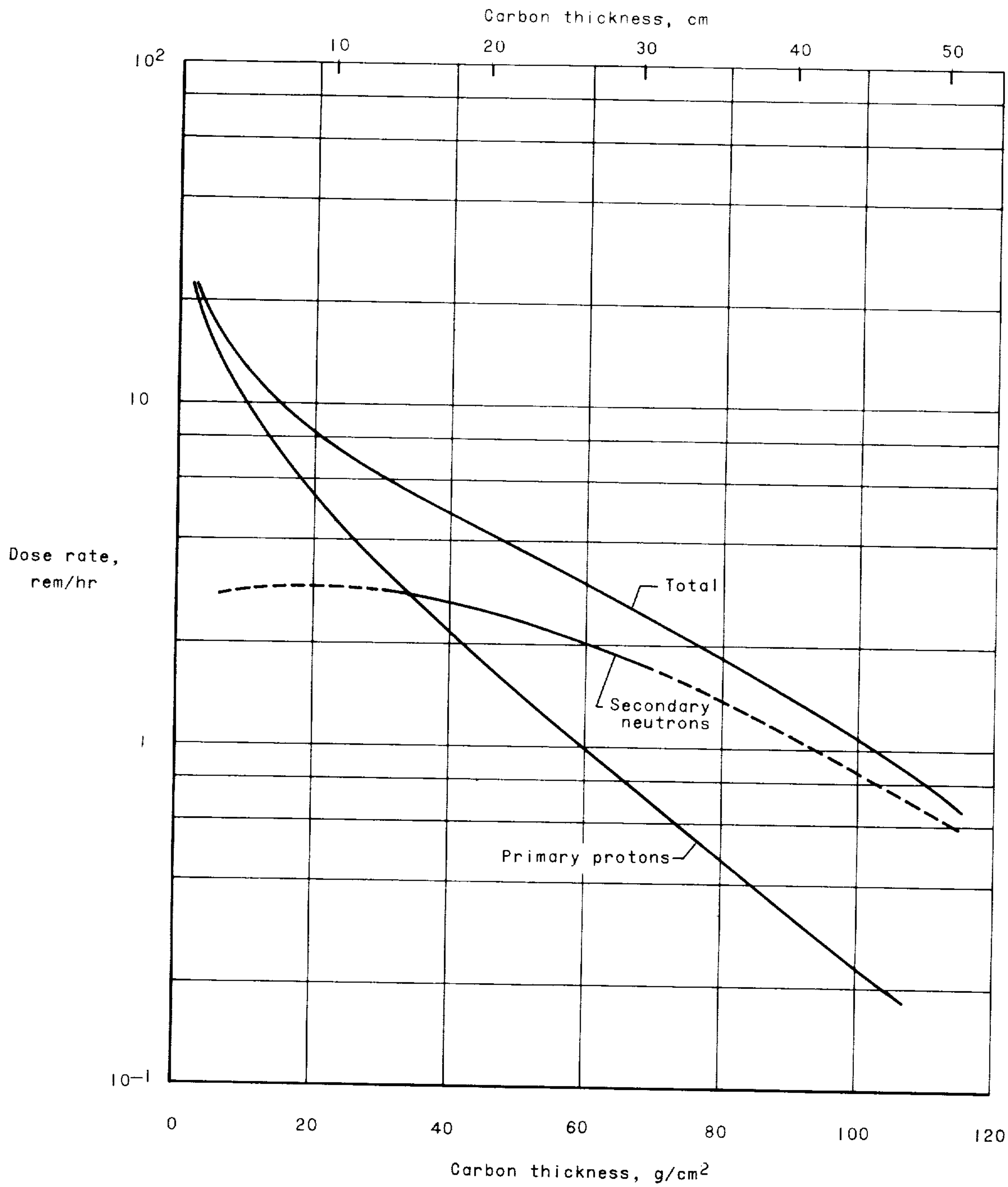


Figure 7.- Calculated dose rates due to penetrating protons and secondary neutrons behind various thicknesses of carbon shield in the heart of the inner Van Allen belt as given in reference 27.

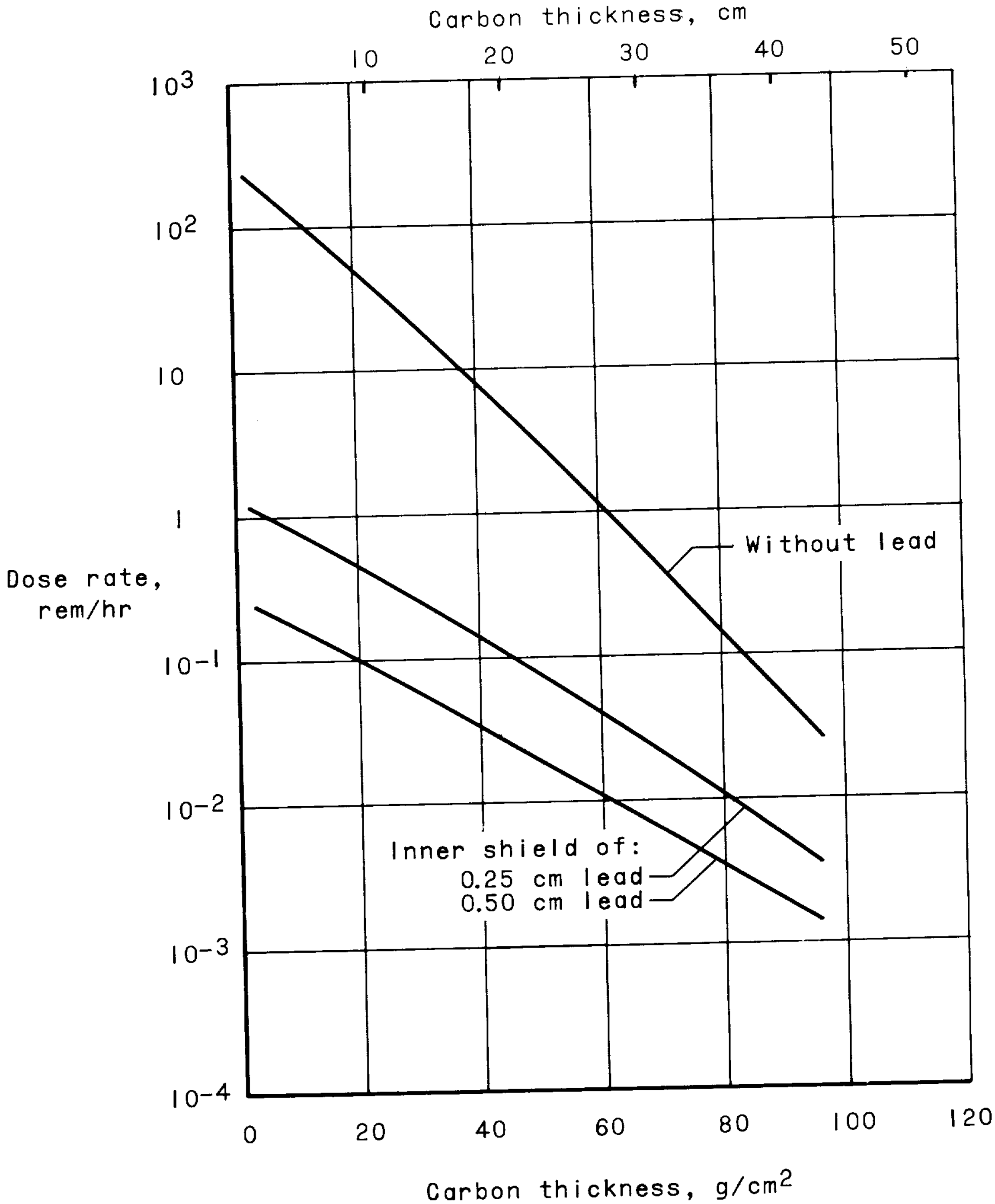


Figure 8.- Dose rate due to secondary X-rays from electrons in the outer Van Allen belt for various thicknesses of carbon shield with and without an inner shield of lead. (From ref. 28.)

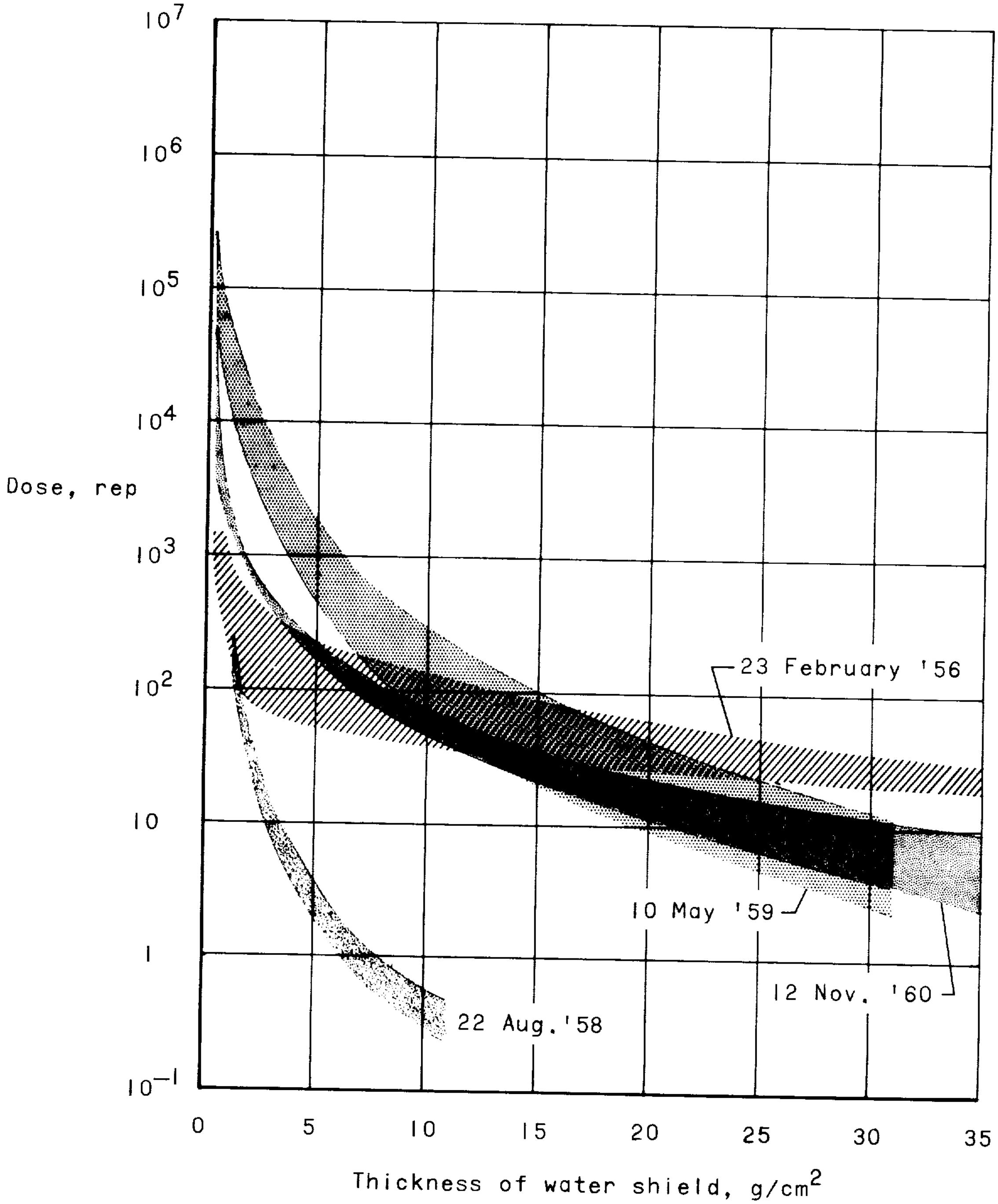


Figure 9.- Estimates of upper and lower limits of accumulated doses in the center of spherical water shields for several solar proton events as presented in reference 9.

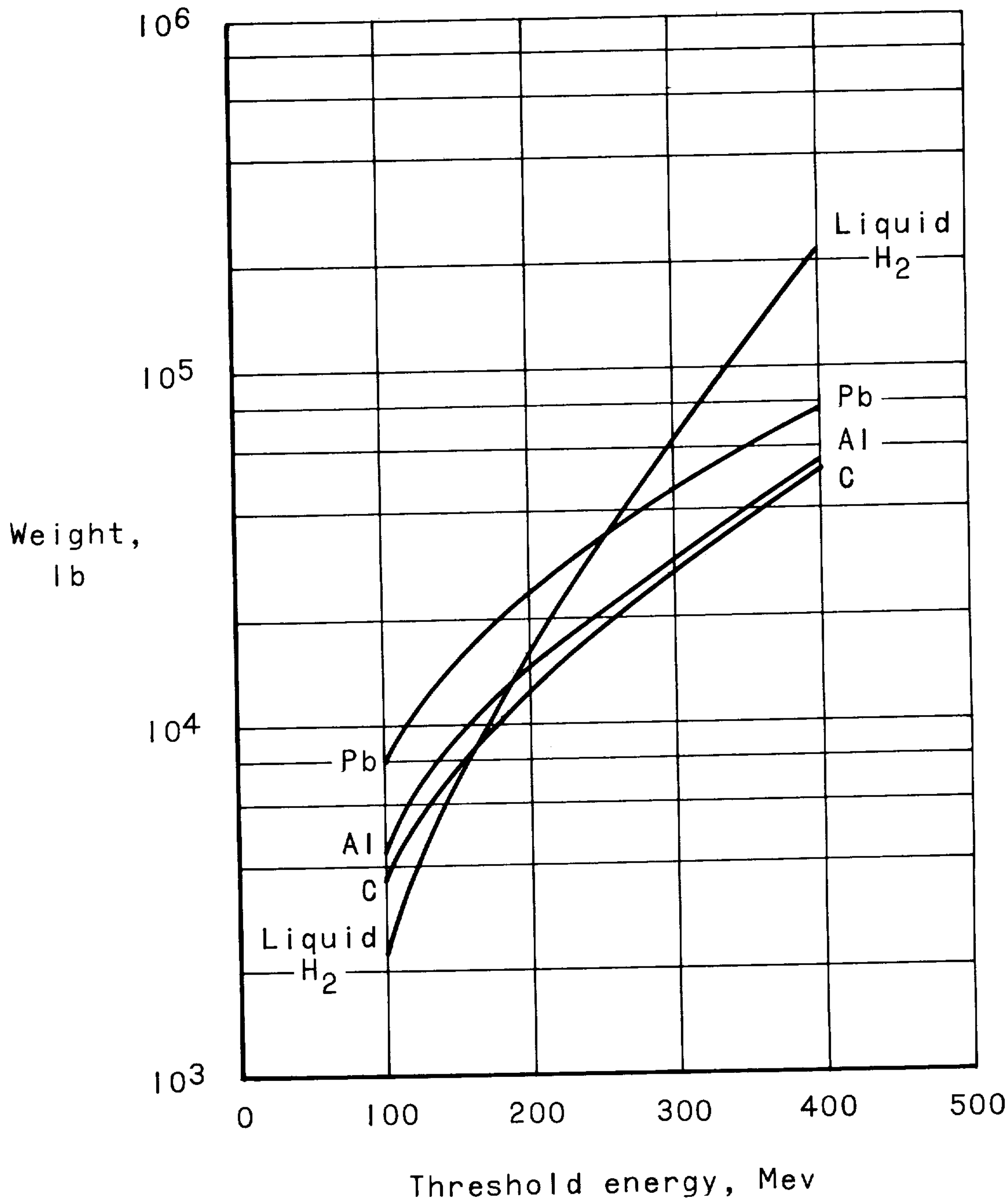


Figure 10.- Comparison of weights of spherical shields of different materials as given in reference 28. Inner radius of shield is 4 feet, threshold energy is maximum energy of proton that will be completely stopped by shield.

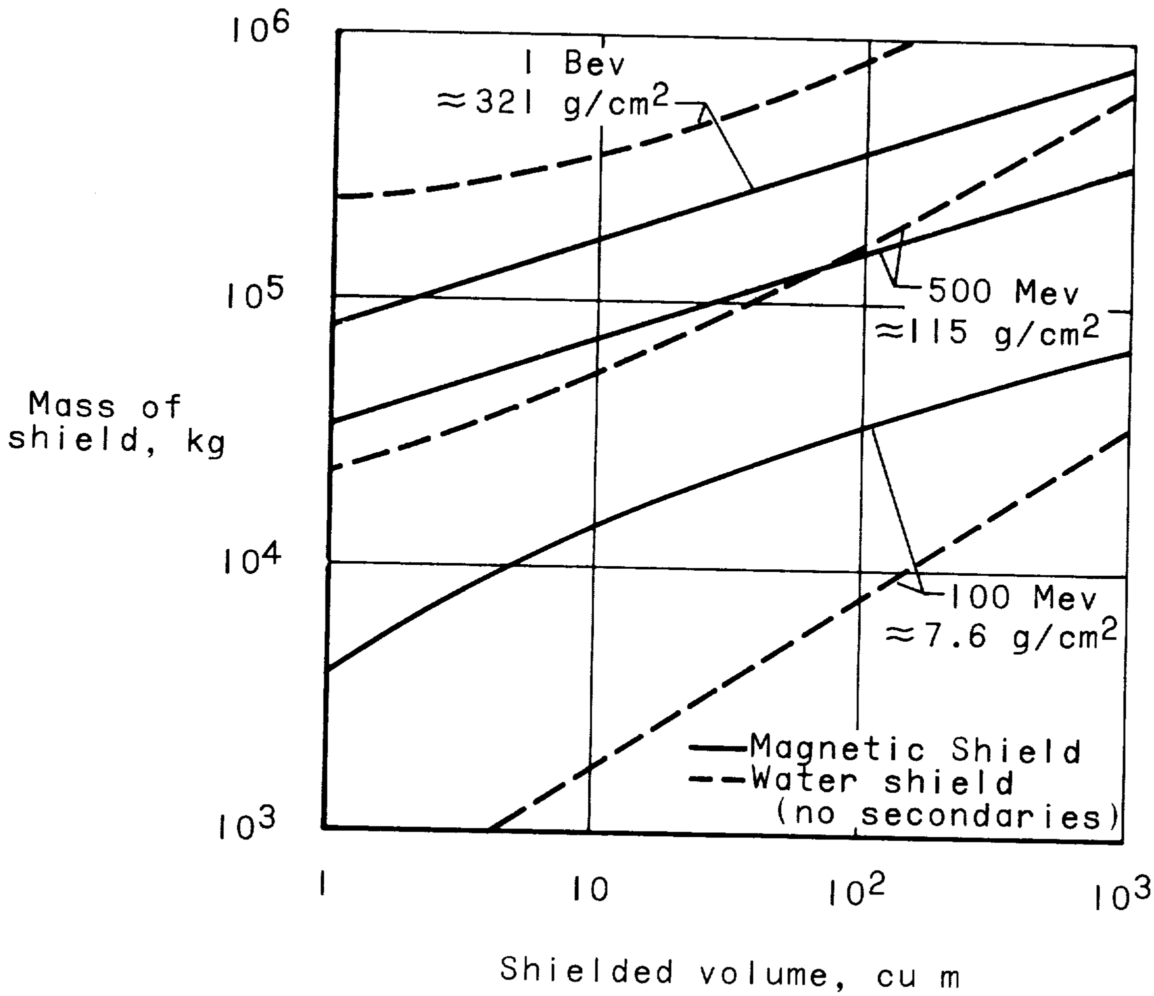


Figure 11.- Comparison of mass of water and magnetic shields required to shield various spherical volumes against protons with energies up to the values shown as given in reference 38.